# CFRP STRENGTHENED CFST COLUMNS UNDER VEHICULAR IMPACT

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## ABSTRACT

Concrete filled steel tubular (CFST) columns are increasingly used in bridge piers and high-rise buildings due to their excellent axial load bearing capacity. These columns may experience severe damage or failure due to transverse impact of vehicle collisions. In this study, numerical investigation is carried out to evaluate the effect of carbon fibre reinforced polymer (CFRP) strengthening CFST columns under vehicular impact. The CFRP composites damage mechanisms are simulated to account four different failure criteria. The cohesive elements are introduced as interface element to properly simulate the adhesively bonded regime. Simplified vehicle model is also developed to represent real vehicle behaviour. The FE analysis results show that externally bonded CFRP composites improve the impact resistance capacity compared to bare CFST column.

## KEYWORDS

CFST columns, CFRP, vehicular impact, numerical simulation.

## INTRODUCTION

Concrete filled steel tubular (CFST) columns provide enhanced structural capacity compared to RC or hollow steel tubular columns. In recent years, these columns are widely used in bridge piers. The early researches have shown that the vehicular or ship impact to the axial load bearing members of bridges is one of the major causes of bridge failure in USA (Wardhana and Hadipriono 2003; Briaud and Hunt 2006). Thus, strengthening/retrofitting of CFST columns may require minimising the damage and failure of bridge columns subjected to accidental vehicular collision. Strengthening of RC structures with externally bonded carbon fibre reinforced polymer (CFRP) is already a proven smart technique over conventional options. However, in recent years, researches are focusing on strengthening/retrofitting metallic structures with CFRP wrapping. Extensive experimental tests and numerical analyses are conducted to explore the potentiality of CFRP strengthened steel members subjected to static loadings (Fawzia *et al*. 2006; Fawzia *et al*. 2007; Shaat and Fam 2009; Fawzia 2013; Kabir *et al*. 2014; Fawzia and Shahanara 2014; Kabir *et al*. 2015). However, research is very limited on the behaviour of CFRP strengthened steel and CFST structures under dynamic loadings such as transverse impact loading (Chen *et al*. 2014; Alam and Fawzia 2015; Alam *et al*. 2014; Alam *et al*. 2015). This study attempts to evaluate the performance of CFRP strengthened full scale bridge column subjected to realistic vehicle impact. Simplified vehicle model is developed and validated with early study. Initially CFRP strengthened CFST column models are validated with available test results in the literature (Chen *et al*. 2014). The validated models are extended to full scale bridge column models and the impact simulation is performed using spring-mass system vehicle model. Both column and vehicle deformations are considered during the simulation as observed in practical situation. The results are presented in terms of impact force and maximum lateral displacement of columns.

## SPRING-MASS SYSTEM VEHICLE MODEL

The simplified spring-mass vehicle model proposed by Al-Thairy 2012 is modelled in ABAQUS/ Explicit and validated with experimental, analytical and, early FE analysis. The spring-mass vehicle model consists of a massless rigid surface, a nonlinear spring and a solid mass to represent vehicle weight as shown in Figure 1. The detail of modelling procedure has been discussed in Al-Thairy 2012. The nonlinear spring is modelled to define the load-deformation behaviour of vehicle during impact simulation. The validation of spring-mass vehicle model is conducted by comparing maximum contact force-displacement results with vehicle full frontal impact tests data available in US National Highway Traffic Safety Administration (NHTSA, 2011) and previous FE analysis (Al-Thairy 2012). The contact forces of vehicle frontal crush tests are estimated by Al-Thairy (Al-Thairy 2012) using the proposed equations (Campbell 1974; Jiang *et al*. 2004) and vehicle frontal crush data from NHTSA. The estimated impact force-displacement curves are used as input parameters to simulate nonlinear spring behaviour. Figure 2 shows the contact force-displacement graphs of three different vehicles used to model spring-mass vehicle model. The validation of spring-mass vehicle models are presented in Table

1 by comparing maximum impact force and vehicle crush distance with test results (NHTSA, 2011) and previous FE simulation (Al-Thairy 2012). The spring displacement values in Table 1 represent the vehicle crush distance of frontal impact tests. Good agreements are found for all three vehicles with similar contact forces and spring displacements compared to estimated impact forces and vehicle crush distances.

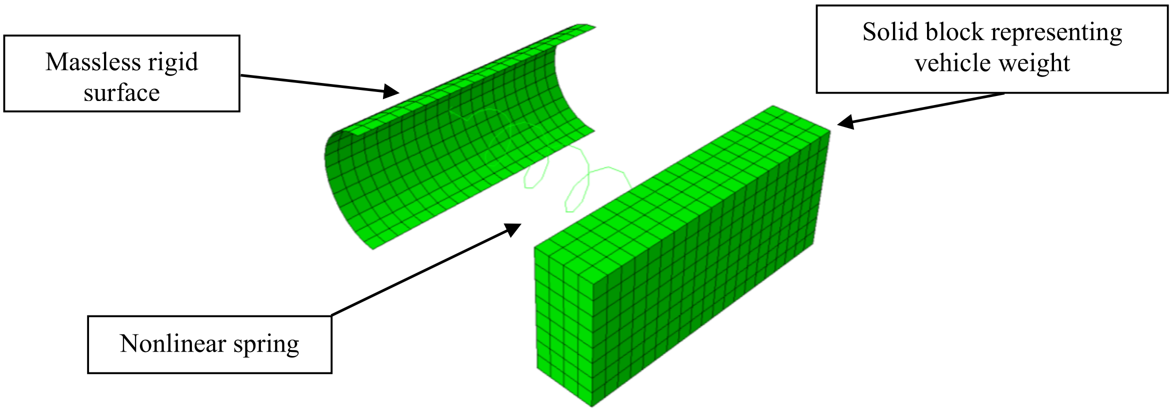



Figure 1 Spring-mass system vehicle model

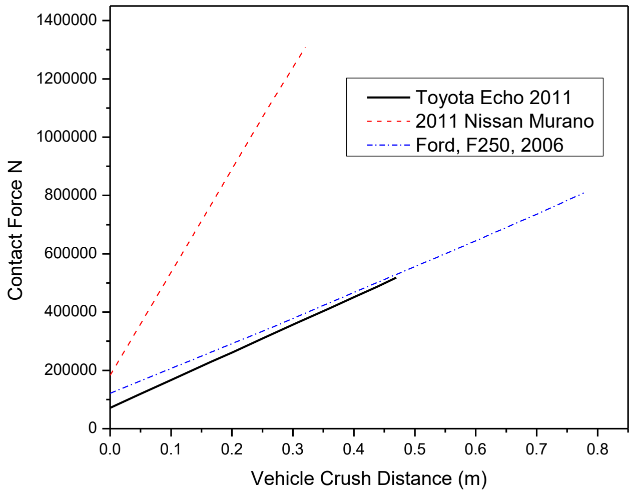



Figure 2 Contact force-vehicle crush distance curves of different vehicle to represent spring-mass vehicle model

Table 1 Validation of spring-mass vehicle model

| Test reference | Vehicle model | Vehicle mass (kg) | Impact velocity (m/s) | Crush distance (m) | Impact force (kN) | Previous study (Al-Thairy 2012) | | Current study | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Impact force (kN) | Spring displacement (m) | Impact force (kN) | Spring displacement (m) |
| NHTSA Test No. 3647(NHTSA, 2011) | Toyota Echo 2001 | 1136 | 15.63 | 0.464 | 515.771* | 525.15 | 0.449 | 538 | 0.477 |
| NHTSA Test No.: MB5208, 2011(NHTSA, 2011) | 2011 Nissan Murano | 2000 | 15.56 | 0.322 | 1319.43* | 1295 | 0.315 | 1310 | 0.323 |
| NHTSA Test No.5820 (NHTSA, 2011) | Ford, F250, 2006 | 3054 | 15.47 | 0.78 | 1050** | 809.03 | 0.762 | 823 | 0.77 |

*Calculated results from Ref. (Al-Thairy 2012); **Test results from NHTSA Test.

The validated spring-mass system model is used to represent full scale numerical vehicle model. The Chevrolet C2500 Pick-Up properties will be used in spring-mass system model to simulate impactor vehicle. The early study has shown (Al-Thairy 2012) that impact force-vehicle crush displacement characteristics of Chevrolet C2500 Pick-Up impacted on rigid column is bilinear as shown in Figure 3. The stiffness of vehicle is low until the vehicle front crushes to engine box which is $K_1$ in Figure 3. Once the engine box is in contact with the rigid column, stiffness is very high ($K_2$) due to the stiffer engine box. Al-Thairy has shown that the stiffness $K_1$ of the bilinear vehicle model is mainly depends on the contact width of the column (Al-Thairy 2012). In this current study, full scale numerical column with outer diameter 300 mm is considered which is very similar to the width of column UC 305 x 305 x 118 used in Al-Thairy study. Therefore in this work, $K_1$ and $K_2$ values are selected as 510 kN/m and $46.8\times10^3$ kN/m respectively obtained from the Chevrolet C2500 Pick-Up and rigid UC 305 x 305 x 118 column simulation (Al-Thairy 2012).

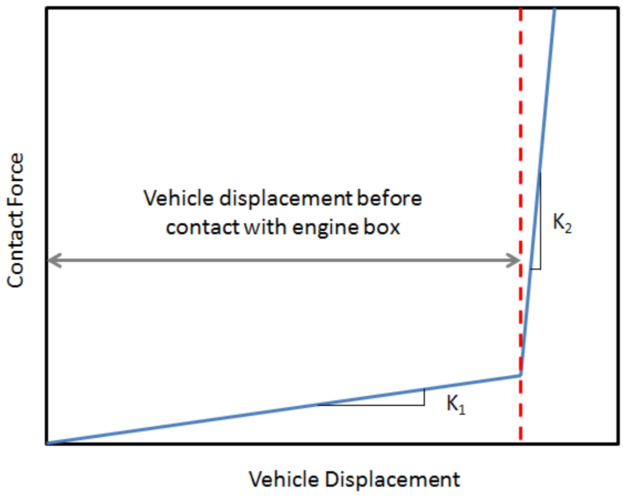
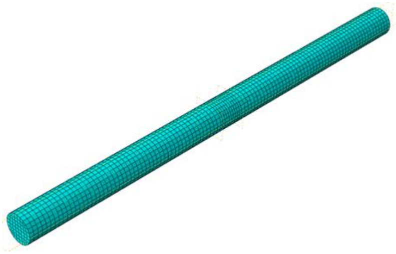



Figure 3 Impact force-vehicle crush displacement characteristics of spring-mass model (redrawn from Ref. (Al-Thairy 2012))

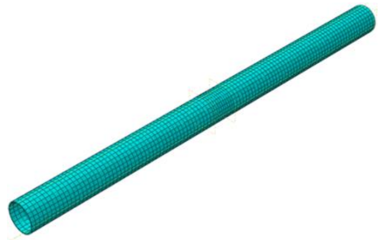
## FE MODELLING OF FULL SCALE COLUMN

### *Model Validation*

Numerical models of bare CFST columns and one layer CFRP strengthened CFST columns are first developed and validated with experiments conducted by Chen *et al*. (Chen *et al*. 2014). The length of the CFST column is 1700 mm with inner diameter 107 mm and wall thickness 3.5 mm. The detail of specimens and experimental set-up can be found elsewhere (Chen *et al*. 2014). Figure 4 shows the FE model of strengthened CFST column subjected to transverse impact loading. The core concrete is modelled considering the confinement effect and strain-rate effects as discussed in the literature (Richart and Brandzaeg 1928; Mander *et al*. 1988; CEB-FIP 1990; Hu *et al*. 2003). The steel tube is modelled using isotropic classic metal plasticity model by considering elastic-plastic behaviour and strain rate effects of steel material. Cohesive elements are used to model epoxy adhesive between the CFRP layer and steel tube outer surface. Traction-separation law available in ABAQUS (SIMULIA 2011) is deployed to define the failure behaviour of cohesive elements. The continuum shell elements are selected to model CFRP sheet. Well known "Hashin" failure criteria are considered to define the failure of CFRP materials (Hashin and Rotem 1973; Hashin 1980). The material properties provided in Chen *et al*. (Chen *et al*. 2014) are used to model steel, core concrete and CFRP sheet. The adhesive properties are selected after a sensitivity analysis as no adhesive properties are mentioned in experimental study (Chen *et al*. 2014). The validation of bare CFST and CFRP strengthened CFST columns subjected transverse impact loading is shown in Figure 5. Good agreement is found between initial peak impact forces for both columns (Figure 5(a) and (b)). Good matching between the lateral displacement-time curves of both bare and strengthened columns are noticed as presented in Fig. 5.



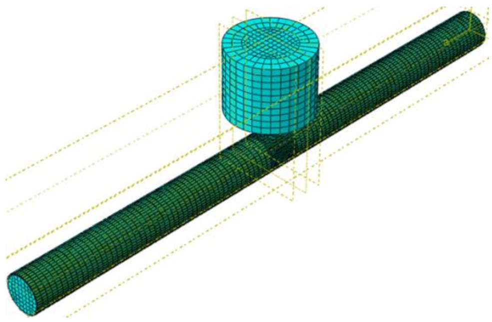
Step 1: Core concrete



Step 2: Steel tube

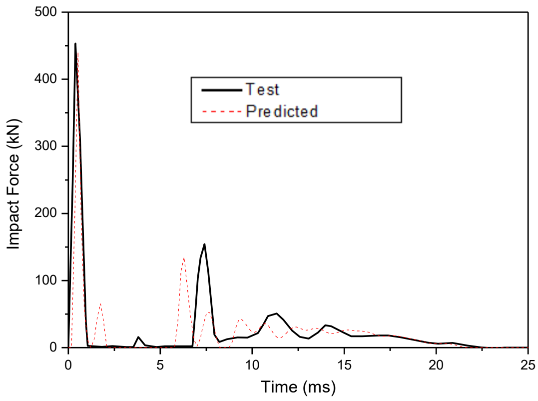
Step 3: Epoxy adhesive

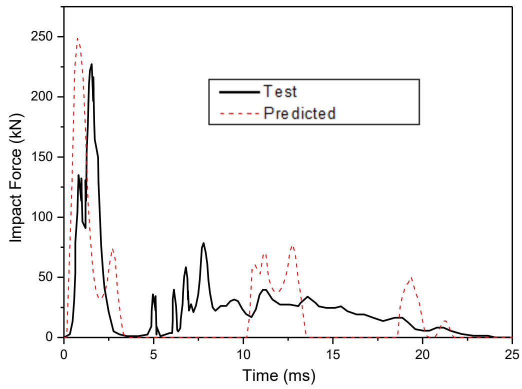
Step 4: CFRP laminate



Step 5: Impactor mass

Figure 4 Detail of FE model

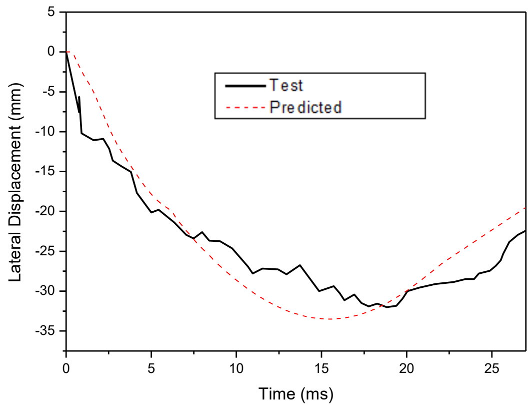


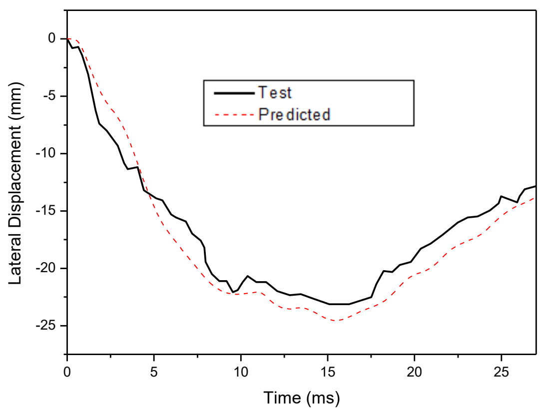




Impact force-time comparison

(a) unstrengthen

(b) one layer CFRP strengthened




Lateral displacement time comparison

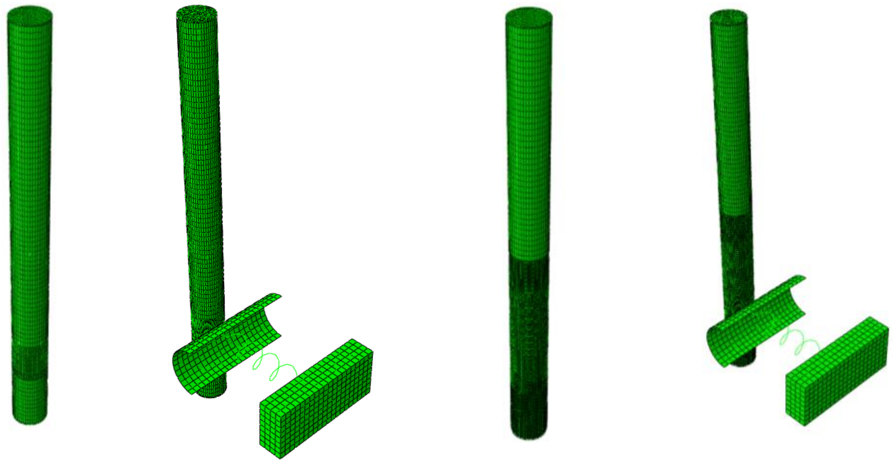
(c) unstrengthen

(d) one layer CFRP strengthened

Figure 5 Validation of FE models

### *Full Scale Column Model*

The validated CFST and one layer CFRP strengthened CFST column models are converted to full scale columns by increasing the column outer diameter 300 mm and length 4000 mm as shown in Figure 6. The validated spring-mass vehicle model representing Chevrolet C2500 Pick-Up is used as an impactor to simulate real vehicle-column interaction subjected to accidental impact (Figure 6(c)). The bottom end of column is fixed boundary condition where the top end is pinned to represent a bridge columns. The impact height is selected as 750 mm from the bottom of the column which is fairly similar to the actual height of Chevrolet C2500 Pick-Up front bumper. Only half of the column length is strengthened in this study to investigate the effects of CFRP strengthening subjected to accidental vehicular impact as shown in Figure 6(b).

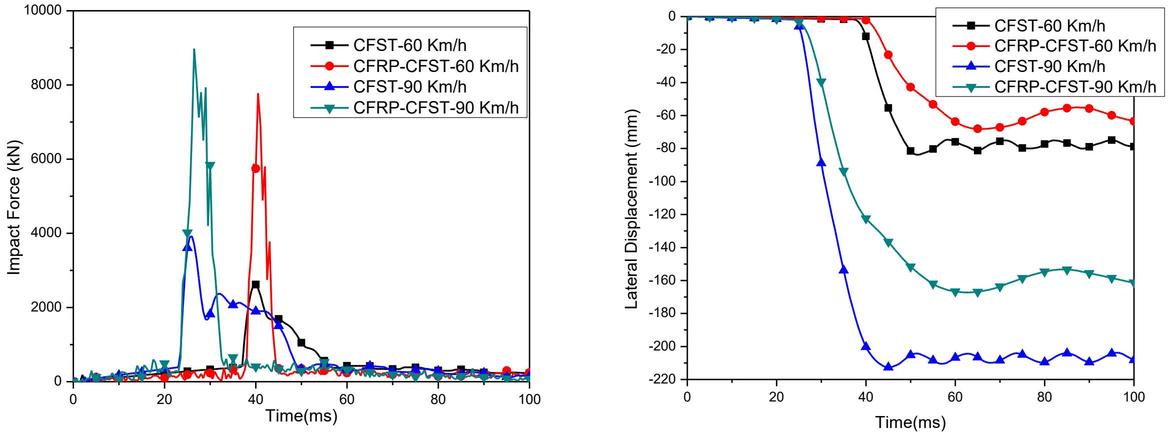


(a) Bare CFST column (b) CFST column with vehicle model (c) CFRP strengthened CFST column (d) CFRP strengthened CFST column with vehicle model

Figure 6 Full scale columns with spring mass vehicle model

## RESULTS AND DISCUSSIONS

The structural responses of bare and strengthened CFST columns are investigated in terms of impact force-time histories and maximum lateral displacement-time curves. The speed of vehicle is varied from 60 to 90 Km/h. Figure 7(a) depicts the impact force-time curves comparison of bare CFST (CFST in Figure 7) and strengthened CFST (CFRP-CFST in Figure 7) columns subjected to 60 and 90 Km/h impact velocities. It is noticed that initial impact force is very low until 36 milliseconds impact time for columns due to 60 Km/h impact velocity. This is due to the low initial stiffness of spring-mass vehicle model as shown in Figure 3. Once the spring displacement reaches to the distance of engine box of vehicle then the peak impact force rises sharply due to the stiff material behaviour of engine box. In case of 90 Km/h speed, the sharp increase of peak impact force occurs at 20 milliseconds due to the higher speed of vehicle. The peak impact forces of strengthened columns are higher than the bare CFST columns as shown in Figure 7(a). This may be due to the increase of the global stiffness of CFRP strengthened columns than the bare CFST columns. Figure 7(b) shows lateral load-time histories of bare and strengthened columns under 60 and 90 Km/h impact velocities. CFRP strengthened CFST columns pose improved impact resistance capacity by minimising maximum lateral displacement 18.7% and 21.35% subjected to 60 Km/h and 90 km/h impact velocities respectively. It is also observed that the externally bonded CFRP wrapping system also delaying the maximum lateral deflection by shifting the peak deflection point at higher impact time compared to bare CFST columns.




(a) (b)

Figure 7(a) impact force-time history comparison, (b) lateral displacement-time history comparison of bare and CFRP strengthened CFST columns

## CONCLUSIONS

In this work, realistic simplified spring-mass vehicle model is developed and validated with earlier study. The three dimensional full scale bare and CFRP strengthened CFST column models are developed to investigate the CFRP wrapping effects under vehicular impact loading. The core findings from this current study are as follows:

- Simplified vehicle model is developed and validated successfully to simulate the realistic vehicle behaviour. The accuracy of this model is acceptable and the computation time is very low compared to full scale FE vehicle model.
- The bare and CFRP strengthened CFST column models are developed and validated with the experimental tests. The results show good agreements in impact force-time histories and maximum lateral displacement-time histories.
- The full scale column models are presented to represent real bridge columns. The transverse impact analyses results show that the peak impact force of strengthened columns increase significantly compared to bare CFST columns.
- The reduction of maximum lateral displacements of strengthened columns has been noticed due to strengthening effects. Thus, CFRP strengthening of CFST columns can be a promising strengthening/retrofitting technique to prevent failure or minimise damage of CFST bridge columns subjected to accidental vehicular impact.

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